Combined Squark and Gluino Mass Bounds from LEP Data

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Under the assumption of gaugino mass unification at a high scale, chargino and neutralino masses depend on the value of the gluino mass, which itself becomes a function of squark masses through self-energy corrections. We demonstrate that this leads to combined bounds on squark and gluino masses from the limits on chargino, neutralino and Higgs boson masses obtained in the CERN LEP-1 and LEP-1.5 runs. These bounds turn out to be comparable to those obtained from direct searches at the Fermilab Tevatron and may be expected to improve as LEP energies go higher.

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Searches for supersymmetric partners of known particles (sparticles) are high priority items at particle accelerators. The non-discovery of such sparticles constrains supersymmetric models, such as the popular Minimal Supersymmetric Standard Model (MSSM) (for reviews, see [1–3]). The direct searches for strongly-interacting sparticles — squarks and gluinos — in $p\bar{p}$ collisions at the Fermilab Tevatron have led to well-known bounds on the masses of these sparticles. Direct as well as indirect searches for electroweak sparticles — including charginos and neutralinos — in e^+e^- collisions at the CERN LEP collider have also yielded constraints on the MSSM parameter space. However, the links between these two classes of sparticles have not been fully explored in previous analyses [4].

In this letter, we point out that bounds on chargino and neutralino (and Higgs boson h^0) masses from the LEP data can be translated into bounds on the squark-gluino mass plane similar to those obtained from the direct Tevatron searches. The crucial features of this analysis are (a) the assumption of gaugino mass unification at a high energy scale [5], which relates the gluino mass $M_{\tilde{g}}$ to the soft supersymmetry(SUSY)-breaking parameters M_1, M_2 in the $SU(2)_L \times U(1)_Y$ sector, and (b) the observation that the gluino mass (and hence M_1, M_2) which determines the chargino and neutralino masses at the different energy scales explored by the LEP experiments is a *running* mass driven by squark loops which differs significantly (by ~ 50–$100\,\mathrm{GeV}$) from the physical mass probed at the Tevatron.

Incorporating gaugino mass unification, chargino and neutralino mass-matrices depend upon the three parameters: the 'gluino mass', μ and $\tan\beta$. (Here μ is the Higgsino-mixing parameter and $\tan\beta$ is the ratio of vacuum expectation values of the two scalar doublets in the theory.) However, the 'gluino mass' parameter here is actually the gluino mass $M_{\tilde{g}}(\sqrt{s})$ evaluated at the LEP energy-scale $\sqrt{s}$ [6]. It is a function of both the physical gluino mass $M_{\tilde{g}}$ and the squark masses and couplings (through radiative corrections) [7]. Thus chargino and neutralino masses and couplings should be considered functions of $M_{\tilde{g}}, \mu, \tan\beta$ as well as the mass-parameters of the squark sector. In principle, this brings into play the full set of inputs which go into the construction of the squark mass-squared matrices [8,9]; *i.e.*, the soft SUSY-breaking masses $m_{\tilde{q}_L}, m_{\tilde{q}_R}$ of left and right squarks respectively and $A_{\tilde{q}}$, the trilinear squark coupling, *for each flavor*. This means that the parameter space that should be considered when determining constraints from LEP data must be expanded from the traditional $M_{\tilde{g}}, \mu, \tan\beta$-parameter set to incorporate many new independent inputs from the squark sector.

The above proposition is rather cumbersome, so all the soft SUSY-breaking squark masses at the weak scale will be set to a common value, $m_{\tilde{q}}$, and all the trilinear couplings $A_{\tilde{q}}$ set to zero. This is employed in the Tevatron analyses [10,11], and we will follow their example here, in part to facilitate comparison of our LEP constraints with those from the the Fermilab Tevatron – the main thrust of this letter. We will comment on the effects of relaxing these assumptions when appropriate. The entire squark sector is thus represented by the single parameter $m_{\tilde{q}}$.

The LEP-1 experimental constraints imposed on the MSSM (with the additional assumptions described above) are the following [12]:

1. The sparticle contribution to the Z^0 boson width. This must be less than the difference between the Standard Model (SM) prediction and the experimental value at 95% CL — roughly 23.1 MeV.

2. The partial decay width of the Z^0 boson to a pair of lightest neutralinos (LSP's). This contributes to the invisible width, and thus must be less than the difference between the experimental number at 95% CL and the SM prediction with 3 neutrino generations — about 8.4 MeV.

3. The branching ratio of the Z^0 boson to any pair of dissimilar neutralinos. Direct LEP searches for such event topologies among the millions of Z^0-decays tallied thus far restrict this to be less that 10^{-5} [13].

4. The physical masses of all the squarks. All charged sfermions must have masses larger than $M_Z/2$. Sleptons do not directly enter into our analysis and so we set their masses to be very heavy.
5. The combined masses of the CP-odd pseudoscalar and CP-even lighter scalar Higgs bosons. The decay channel $Z^0 \to h^0 A^0$ is strongly constrained by LEP searches basically requiring that $M_A + M_h > M_Z$.
6. The partial width for the Bjorken process with the lighter scalar Higgs boson h^0. This should not exceed the corresponding partial width for the Z^0-decay to a SM Higgs boson, where the mass of this SM Higgs boson is given by the experimental bound of 65.2 GeV [14].
We also impose one additional constraint from LEP-1.5:
7. The mass of the lighter chargino. The unsuccessful direct LEP-1.5 searches for chargino pair production mean that the chargino mass must be greater than 67.8 GeV, provided the chargino-LSP mass difference exceeds 10 GeV [15]. Direct searches for chargino pairs in the Z^0 decays at LEP-1 also require the lighter chargino mass to be above 45 GeV, consistent with constraint 1. above. In fact, the inclusion of the LEP-1.5 constraint renders constraint 1. mostly superfluous, save in the narrow region of the parameter space where the chargino and the LSP are almost degenerate.

Many features of constraints 1.-3.,7. follow from the structure of the chargino mass matrix (see [2] for its form and [16] regarding higher-order corrections not included here). The lighter chargino mass eigenvalue (absolute value) is lowered as $\tan\beta$ increases; thus chargino mass limits for low $M_{\tilde{g}}$ tend to disallow large values of $\tan\beta$. Similarly, constraint 4. is dependent on the structure of the sfermion mixing matrices — as $|\mu|\ \cot\beta(|\mu|\ \tan\beta)$ increases (with $A_t = A_b = 0$), the lighter stop (sbottom) mass decreases. Constraints 5. and 6. above relate to the Higgs sector of the MSSM. At tree level, the masses of the five Higgs bosons are fixed by inputting $\tan\beta$ and the mass of the CP-odd A^0 [17]. In general, consideration of the Higgs sector would introduce M_A as another significant input parameter which must be included in the analysis of the LEP data; however, here we will restrict ourselves to the case in which $M_A{\sim}1$ TeV. In this case though M_h can still be relatively light and constraint 6. can still rule out regions with $\tan\beta$ close to unity and $|\mu|$ less than 300 GeV or so. If, on the other hand, one demands that A^0 be quite light, the allowed parameter space is much more constrained.

Next consider briefly the effects of changing the squark-sector input assumptions. In SUGRA models [18], a favored scenario is for $m_{\tilde{t}_L}$ and $m_{\tilde{t}_R}$ to be significantly smaller than the other soft SUSY-breaking $m_{\tilde{q}}$'s (with the $m_{\tilde{t}_R}$ also significantly smaller than $m_{\tilde{t}_L}$). We find that our results for high gluino masses are not very sensitive to this change, since, as mentioned earlier, the presence of the top quark mass in the terms of the stop mass-squared matrix buoys up the physical stop masses for low values of $m_{\tilde{t}_L}$ and $m_{\tilde{t}_R}$. In the pure MSSM, however, *all* the soft SUSY-breaking squark masses are independent inputs [19], and we find that lowering $m_{\tilde{b}_L}$ and $m_{\tilde{b}_R}$ below the common input for the first and second generation squarks ($m_{\tilde{q}}$) *does* raise the LEP lower limit on $m_{\tilde{q}}$ significantly for high gluino masses. For low gluino masses, our results are sensitive to lowering the stop inputs though their effect on the h^0 mass as described below. Non-zero $A_{\tilde{q}}$'s only significantly affect third generation squark masses and couplings since they appear as $m_q A_{\tilde{q}}$, where m_q is the mass of the relevant *quark*. For the case of stops (and, to some extent, sbottoms) we have verified that the effects of varying $A_{\tilde{q}}$ in the range –2 TeV to +2 TeV more or less duplicate those obtained by variation of $|\mu|$ in the range 0 to 1 TeV. This is as expected since the off-diagonal term in the stop mass-squared matrix has the form $m_t(A_t - \mu\cot\beta)$. Thus variation of $|\mu|$ to a large extent obviates the need to vary A_t and A_b.

In this present work, we wish to concentrate on constraints in the $m_{\tilde{q}} - M_{\tilde{g}}$ plane [20], allowing other input parameters to have any value in their generally-accepted ranges, which we take to be: $0 < |\mu| < 1$ TeV and $1 < \tan\beta < 35$ [21]. The LEP constraints clearly disfavor light $m_{\tilde{q}}$'s or $M_{\tilde{g}}$'s taken individually. Further, squarks alter the running gluino mass leading to combined mass bounds rather than separate ones.

Our results are shown in Figure 1(a) which illustrates bounds from the seven constraints given above. The shaded region bounded by solid lines is ruled out; the remaining portion is allowed for *at least one value* of μ and $\tan\beta$. The dashed lines show the bounds arrived at (for $\tan\beta = 4$) from searches for squarks and gluinos by the CDF [10,22] and D∅ [11] Collaborations. These trail off into big dots for the regions beyond the published limits. The small-dotted curve in Figure 1 illustrates the region excluded if the lower bound on the chargino mass climbs to 85 GeV (provided the chargino-LSP mass difference is larger than 10 GeV), which is more or less the discovery limit expected from LEP-2. The bounds on the squark-gluino mass plane obtained and obtainable from LEP (again, with the gaugino unification assumption) are seen to be somewhat complementary to those obtained from the Tevatron: LEP covers more of the low $M_{\tilde{g}}$, high $m_{\tilde{q}}$ region than the Tevatron while Tevatron does better in the moderate $M_{\tilde{g}}$, low $m_{\tilde{q}}$ region [23]. LEP is also seen to exclude squark masses below about 70 GeV for all gluino masses. Also, gluino masses much below 180 GeV can be obtained only for large squark masses above 400 GeV [24]. Further note that if we add to this the projected LEP-2 bound that the mass of the chargino lie above 85 GeV, then a gluino mass below about 180 GeV is *ruled out irrespective of squark mass.*

Earlier studies of the LEP [25] (UA1 [22]) constraints have yielded only 45(53) GeV as a lower bound for the squark (gluino) mass. Previous analyses (see for example figure 3 of [16] or Figure 6 of [2]) also show a low $M_{\tilde{g}}$ window for low $\tan\beta$ and small negative values of μ.

There is in fact a razor-thin band of μ-choices (small in magnitude and negative) for quite low gluino masses and for $\tan\beta$ close to 1 which are allowed by the LEP-1 and LEP-1.5 constraints *on the chargino/neutralino sector*. Here the coupling of the Z^0 to a lightest and a next-to-lightest neutralino is heavily suppressed. In the low $m_{\widetilde{q}}$ (and stop mass) 'LEP-1' region of the figure this band is disallowed by constraint 6. on h^0 (which in turn depends on the stop masses), and in the 'LEP-2' region the band is excluded by the chargino mass constaint [26].

As alluded to above, Tevatron excludes a region of moderate gluino masses ($M_{\widetilde{g}} \sim 300\,\text{GeV}$) and low squark masses ($m_{\widetilde{q}} \sim 100\,\text{GeV}$) which is allowed by the LEP constaints, even with the unification hypothesis. It should be noted though that the CDF and DØ analyses have only been presented for fixed values of $\tan\beta$ and μ [10,11,27,28], and hence our analysis is not quite on a par with the assumptions going into their results. A more exact comparison is made in Figure 1(b), in which $\tan\beta = 4$ as in [10,11]. Clearly, the extra region covered by the Tevatron experiments which is not explorable at LEP persists. LEP is also still seen to exclude squark masses below about 71 GeV for all gluino masses. (This lower limit is unchanged for the case of $m_{\widetilde{t}_L} = m_{\widetilde{b}_L} = 0.8 m_{\widetilde{q}}$, $m_{\widetilde{t}_R} = 0.6 m_{\widetilde{q}}$, but rises to roughly 93 GeV for $m_{\widetilde{t}_L} = m_{\widetilde{b}_L} = m_{\widetilde{b}_R} = 0.5 m_{\widetilde{q}}$.) In addition, a lower LEP bound of about 200 GeV on the gluino mass holds for a much larger range of squark masses with $\tan\beta$ fixed at 4 than the case shown in Figure 1 where *all values* of $\tan\beta$ are considered. In fact this bound appears to hold all the way up to a squark mass of 1.5 TeV or more for $\tan\beta = 4$. And for the 'LEP-2' case the lower bound on gluino mass goes as high as 260 GeV for $\tan\beta = 4$.

Finally, we wish to emphasize again that our results rely on the hypothesis of gaugino mass unification; if we give up this idea, then the LEP constraints will have practically no effect on the squark and gluino masses. However, Tevatron data will still give constraints, though not perhaps the same constraints as have been published, since these have also incorporated the gaugino mass unification assumption into the analysis of the cascade decays of squarks and gluinos.

In this letter we have shown that gaugino mass unification and the running of the gluino mass enables LEP bounds on electroweak sparticle production to be translated into mass bounds on the strongly-interacting sparticles. These bounds depend inseparably on both squark and gluino inputs and turn out to be comparable and, in some sense, complementary to those established at the Tevatron from direct searches for squarks and gluinos. Thus, studies of electroweak physics conducted at LEP can be a powerful tools to probe some physics aspects normally thought to be accessible only at a hadron collider.

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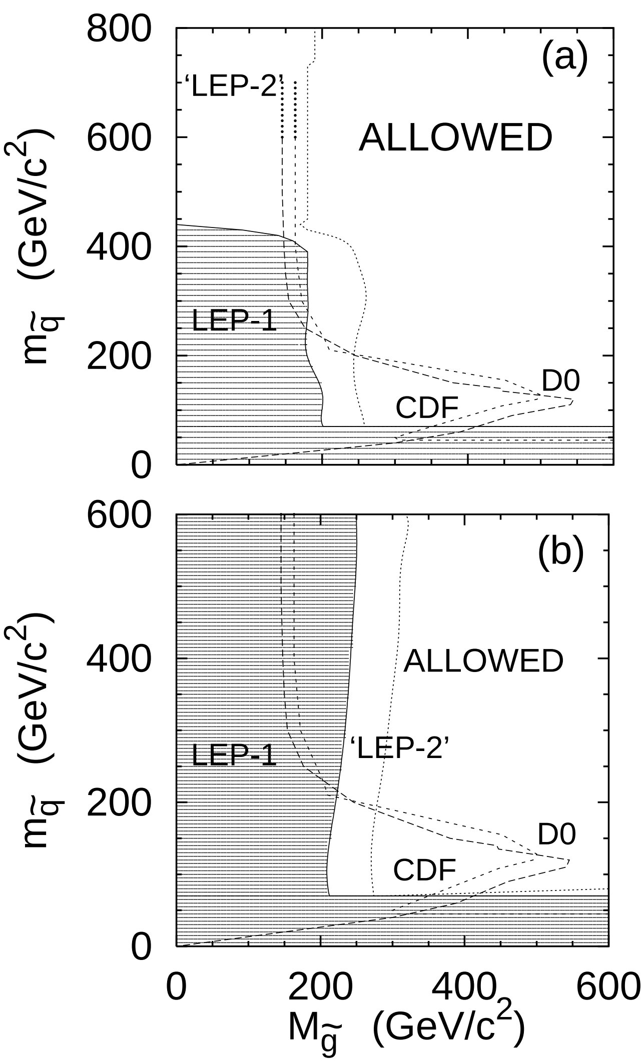

FIG. 1. Illustrating the region in the $m_{\widetilde{q}} - M_{\widetilde{g}}$ plane allowed by LEP constraints. In (a) μ and $\tan\beta$ are varied over their generally-accepted ranges, while in (b) $\tan\beta$ is fixed at 4. The shaded region is ruled out by LEP-1 and LEP-1.5 constraints while the dotted curve delineates the 'LEP-2' region where the chargino mass is always less than 85 GeV. The dashed curves correspond to bounds established by the CDF (short dashes) and D∅ (long dashes) Collaborations for $\tan\beta = 4$, trailing into big dots beyond the published results.